US LHC ACCELERATOR PROJECT

brookhaven - fermilab - berkeley

US-LHC Accelerator Project Office
Fermilab MS-343
PO Box 500
Batavia IL 60510 USA
Fax: (630) 840 8032

8 May 2001

To: Distribution

From: Phil Pfund

Subject: LQX Cryostat Engineering Design Review

The attached report covers the Engineering Design Review (EDR) for the LQX Cryostat.

It incorporates comments on previous drafts by the review committee and has been approved by the US LHC Accelerator Project Manager as of Tuesday 8 May 2001.

Distribution:

FNAL: J. Strait, P. Pfund, J. Kerby, T. Nicol, T. Peterson, T. Page, M. Lamm, F. Nobrega
BNL: S. Plate
LBNL: J. Zbasnik
CERN: T. Taylor, R. Ostojic, G. Kirby, R. van Weelderen, B. Skoczen, G. Trinquart, I. Collins, J.-P. Papis, D. Missiaen, N. Siegel, M. Bona, R. Vuillermet, L. Williams, J.-P. Tock
DOE: B. Strauss, J. Yeck

Engineering Design Review

LQX Cryostat

12 March 2001

Introduction

FNAL is responsible for the cryostats for the IR Interaction Region Quadrupole systems. The FNAL work scope includes:

- Design, development and fabrication of the cryostats.
- Construction of a full-scale model heat exchanger.
- R&D on support structures.
- Construction of a cryostat for the full-scale prototype quadrupole.
- Assembly of U.S.- and Japanese-built quadrupoles (MQXB and MQXA respectively) together with CERN-supplied correction coils to make complete cold mass assemblies, and insert them into the cryostats to produce complete LQX cryoassemblies for all four interaction regions.
- Design and fabrication of the secondary beam absorbers, TAS2 and TAS3 (designated TASA and TASB respectively in optics version 6.3).

This EDR followed a Conceptual Design Review (CDR) that was held on 3 December 1998 and an Interim Design Review that was held on 13 March 2000. The reports, including action items, have been issued for both of these reviews.

This EDR will be followed by a Production Readiness Review (PRR). The PRR will be scheduled to occur after final design is complete and before final production of the cryostats begins. The PRR will include a strategy for fabrication or procurement, quality assurance, and a component test plan. The PRR is planned for July 2001.

The EDR covered the following items in particular:

- Final designs of:
  - the LMQXB (Q2) cold mass, which consists of two MQXB quadrupoles together with an MCBX dipole corrector;
  - the LMQXA (Q1) cold mass, which consists of an MQXA quadrupole together with an MCBX dipole corrector;
  - and the LMQXC (Q3) cold mass, which consists of an MQXA quadrupole together with an MCBXA dipole plus multipole corrector package and an MQSXA skew quadrupole plus multipole corrector package.

- Final design of the LQXA, LQXB and LQXC cryostats including testing to support design decisions.
- Functional Specification and Interface Specification documents that are planned.
- Special equipment for transportation, installation, and alignment in the tunnel at CERN.
- Design concepts that were not explicitly covered during the CDR: support of MQXA (KEK cold mass) and MQXB (FNAL cold mass), 1.9 K heat exchanger and connection of Q2a and Q2b cold masses.

The review did not explicitly cover the design and testing of the MQX IR high gradient quadruples. The MQXB was covered by a separate EDR conducted on 16 March 2000 and the MQXA is the responsibility of KEK. The review did however cover the interfaces of the cryostat to both types of magnet cold masses, corrector magnets, and interconnect between adjacent IR quadrupoles.

The review was conducted at CERN.

Reviewers:

- Phil Pfund, Fermilab, chairman
- Jim Strait, Fermilab
- Ranko Ostojic, CERN
- Glyn Kirby, CERN
- Tom Taylor, CERN
- Rob van Weelderen, CERN
- Blazej Skoczen, CERN
- Gilbert Trinquqrt, CERN
- Ian Collins, CERN
- Jean-Pierre Papis, CERN
- Dominique Missiaen, CERN
- Steve Plate, BNL
- Tom Peterson, Fermilab
- Jon Zbasnik, LBNL

Speakers:

- Jim Kerby, Fermilab
- Tom Nicol, Fermilab
- Tom Page, Fermilab

Others Present:

- Maurizio Bona, CERN
- Raphael Vuillermet, CERN
- Norbert Siegel, CERN
- Fred Nobrega, Fermilab

Summary

An Engineering Design Review (EDR) is to be conducted when most of the R&D is complete and the engineering design has been finalized. For a system to pass the EDR, it must be demonstrated that all of the technical and engineering challenges have been adequately addressed.

The reviewers believe the Fermilab designs of the inner triplet cryostats are sufficiently complete to proceed to the final details necessary to support the Production Readiness Review and the subsequent start of series production.

The reviewers have commented on a number of design items that need attention. The comments are itemized in the following section. Most of the comments relate to design of the interconnects. The Project Manager intends to reconvene some of the reviewers to cover the interconnects in greater detail.

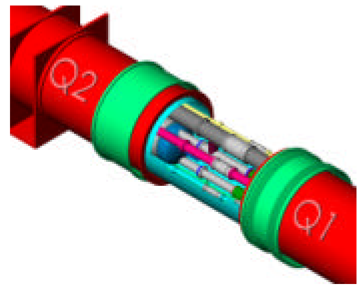
The Project Manager approved the design effort to go forward to address the reviewer's comments and to complete the details necessary for a Production Readiness Review (PRR).

Comments

The following comments were raised by the reviewers and the listed actions are strongly recommended.

1. Interconnect pipe supports

The designers acknowledged that some arrangement for pipe support in the interconnect regions will be required but the design has not yet been developed. Particular concern was expressed with regard to the stability of the long pipes under pressure, and the precision of the alignment of the beam tube across the long interconnects.



<u>Action</u>: Fermilab needs to complete the design for pipe support in the interconnect regions.

2. Stability of tie rods under vacuum loads

Tie rods are required to resist the unbalance vacuum forces on the cryoassemblies. Four tie rods, spaced 90 degrees apart, are connected to the vacuum vessel flanges on opposite sides of each interconnect. In this application, the tie rods are loaded in compression, rather than tension, and are subject to column buckling. The mechanical stability of the rods under the compressive loads induced by the unbalanced vacuum forces was not presented.

<u>Action</u>: Fermilab should complete their analysis of mechanical stability of the tie rods under vacuum loads.

3. Use of automatic welding equipment

CERN intends to use automatic welding equipment to the maximum extent possible. The technical specification for acquiring the equipment calls for a minimum radial clearance of 40 mm and axial clearance of 130 mm. However, it is believed that equipment capable of operating within 40 mm of radial clearance will prove to be unachievable and 45 mm is more likely. For that reason, CERN is now requesting at least 45 mm of radial clearance be designed around all welded joints.

It was stated during the review that not all of the inner triplet pipe welds will meet the request for 45 mm of radial clearance. The most constrained location is near the beam pipe – cold mass differential expansion bellows where the clearance is 30 mm, making automatic welding impossible. Even a manual weld in a radial space as tight as 30 mm would be very difficult to make and test.

Action: Fermilab is evaluating eliminating the beam pipe – cold mass differential expansion bellows which would increase the radial clearance in that area.

Action: Fermilab needs to identify all welds that will fall below the requested clearances of 45 mm radial and 130 mm axial.

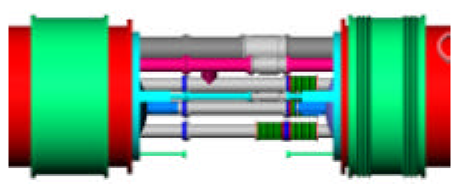
Action: CERN and Fermilab need jointly to address viable solutions to any space-restricted welds.

4. *Interface between cryostat feet and jacks*

CERN is using a different set of jacks for the inner triplet quadrupoles than for the dipole. The dipole jacks have a spherical interface and can resist the axial loads induced by unbalanced vacuum forces. The quadrupole jacks have an elastomer type raising mechanism with a flat interface and can't resist the unbalanced vacuum forces. Tie rods connect each cryostat for the purpose of resisting those forces. The Fermilab design does not yet detail the interface between the cryostat feet and the jacks.

Action: Fermilab needs to provide the details of the interface between the cyrostat feet and jacks.

5. *Interconnect region magnet splices*



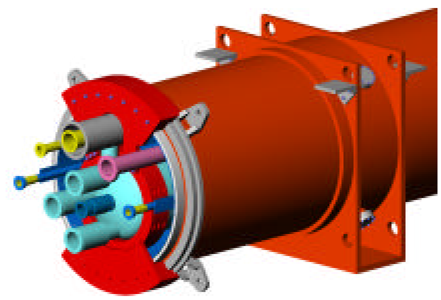
In the interconnect region, the pipe containing the main magnet power bus has a double bellows to allow sufficient access to make a splice. The pipe containing the corrector bus and instrumentation wires has been reduced to a single bellows, thereby reducing the axial length available to make the splices. The necessary length of corrector bus splice has not been determined.

It is important to ensure adequate flow paths area around the splices and their supports in the interconnect for quench venting. This is particularly important at the Q3-DFBX interface where there are only two cold mass pipes.

Action: Fermilab needs to determine the length of the corrector bus splice in the interconnect region.

Action: Fermilab needs to ensure adequate flow area for quench venting at the interconnects.

6. Shipping loads



Fermilab has demonstrated that the cold mass support will withstand 2 g of horizontal load before failure. During shipment the ends of the cold mass will also be restrained through a fixture to the vacuum vessel. It is expected that loads experienced during shipping and handling will range higher than 2 g. The heat exchanger test unit experienced one event of 4 g and one of the reviewers believed ocean shipping loads may be as high as 5 g.

Action: Fermilab needs to include shipping restraints that are capable of isolating the cryoassembly from anticipated shipping loads. The resulting loads on the cold mass support need to be kept below 2 g.

7. BPM feedthrough flanges

The BPM signals will routed out of the cryoassembly through the interconnect sleeve and not through the DFBX along with the rest of the instrumentation. The details of the BPM cable feedthrough flanges have been provided to Fermilab. Two flanges with four connections each are required to accommodate the eight BPM cables.

Action: Fermilab needs to add BPM cable feedthrough flanges to the design of the interconnects.

8. Cold bore temperature in the magnets

CERN requires that the coldest surface seen by the beam through the inner triplet remains below 3 K to provide sufficient background cryopumping of hydrogen. The most apparent solution is to depend on the 1.9 K magnet cold bore as the pumping surface, and to use a beam screen or liner to shadow the pumping surface from synchrotron radiation, which could desorb cryopumped molecules. It is also desirable that the line be kept below approximately 50 K when subjected to beam heating, to avoid desorption of, for example, CO_2 which is present from the initial cooldown. The simplest solution would be to cool the liner by thermal conduction to the cold bore tube, but it has not yet been demonstrated that sufficiently good thermal contact can be achieved in a design which allows insertion of the liner after magnet manufacture. Especially in Q1, where the beam heating is most intense, an actively cooled beam screen at some temperature greater than 3 K may be required. A separate cooling line would need to be provided to service an actively cooled beam screen.

Action: CERN needs to determine if an actively cooled beam screen is required in Q1.

Action: If an actively cooled beam screen is required, Fermilab needs to add piping to supply an actively cooled beam screen in Q1, and LBNL needs to determine if this affects the DFBX design.

9. Cold bore temperature in the interconnects

The short sections of the beam tube in the interconnect regions need to be kept below 3 K as well. Secondary absorbers TAS2 and TAS3 (designated as TASA and TASB respectively in optics version 6.3) are located in IR 1 and 5. The absorbers are cooled with 4.5 K helium but the beam bore passing through them may need to be maintained below 3 K. Fermilab envisions a thermal clamp around the cold bore to cool it to the desired temperature.

Action: Fermilab needs to investigate how to maintain the cold bore at its specified temperature.

10. Drawings

Individuals at Fermilab and CERN have been exchanging hardcopy and electronic drawings on an informal basis as the design of the inner triplet has evolved. Thus far, no drawings have been submitted to the CDD for wider viewing. CERN identified an increasing need for accessible drawings to support planning for transportation and installation. CERN also expressed a need for Q1 drawings to support design integration into the tight spaces of the IP.

Action: Fermilab needs to submit drawings that are critical to support design integration with CERN.

11. Transportation, lifting and handling

Transportation and the lifting and handling associated with it were discussed several times during the review. The full installation scenario of the quadrupoles is the responsibility of CERN, but it was felt that transportation, lifting and handling requirements of the quadrupoles should be included in the tunnel interface specification that Fermilab intends to prepare. The specification should cover the requirements during transportation: on the surface, down the shaft, to the transport vehicle and to the installation location. The specification needs to define pick-up points and handling restrictions. CERN is designing and specifying transport vehicles for the arc dipoles, but modifications would be necessary to accommodate the quadrupoles. Fermilab lifting tools will not be shipped to CERN. Fermilab can provide drawings, but CERN will need to provide their own tools.

There was general concern about the mechanical stability of the cold mass inside the cryostat after thermal cycles, after lifting and after transportation. CERN recommended a simplified dynamic response study of the quadrupole cryoassembly, similar to that done with the arc dipole.

Action: Fermilab needs to prepare the tunnel interface specification. The specification should include transportation and handling criteria and limitations applicable on the surface, down the access shaft, to the transport vehicle, and to the installation location.

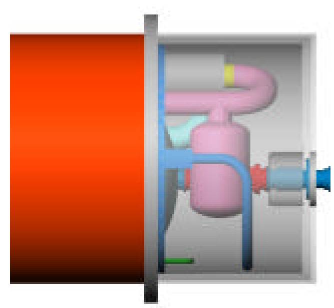
Action: Fermilab is requested to perform a simple dynamic response study of the quadrupole cryoassembly.

Action: Fermilab will transport Q2P1 around their site and take measurements to obtain some data on the mechanical stability of the cold mass.

Action: CERN needs to arrange for necessary lifting and handling tools to be used at the LHC.

Action: CERN needs to develop the full installation scenario for the quadrupoles, from receipt at CERN to final installation in the LHC.

12. IP end of Q1

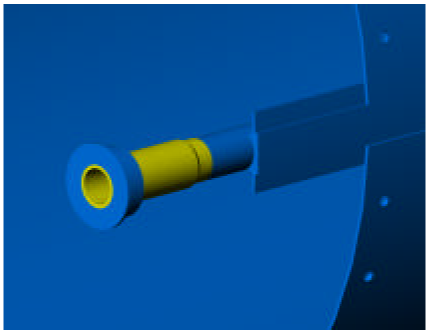


It was pointed out that space is at a premium at the IP end of Q1. The Q1 is surrounded by the forward shielding of the experiments. CERN is evaluating whether to move the BPM outside of the vacuum vessel. The Q1 vacuum vessel would need to be shortened to make room, but more design detail is needed at the IP end of Q1 to support the evaluation. The warm to cold transition with a stay-clear region of 115 mm radially and 500 mm axially will define the length of the vacuum vessel extension.

Action: Fermilab is requested to propose a "shortest possible" IP end of the Q1 cryoassembly on the assumption that the BPM is located outside of the vacuum vessel.

Action: CERN needs to provide designs for the warm-to-cold transition, including stay-clear areas to Fermilab.

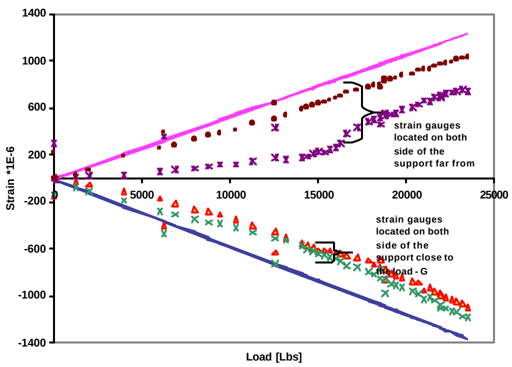
13. Stability of thermal shields



A couple of aspects of the stability of the thermal shields were discussed. It was felt necessary to check the buckling resistance of the extrusion piping under pressure at both maximum operating (22 bar) and test (27.5 bar) pressures. The extrusion has a thermal fin and would be quite stiff in the lateral direction of the fin, but much less stiff in the transverse direction to the fin. It was also suggested to check for stability against collapse of the thermal shield due to eddy currents in the aluminum shield, especially during a quench.

Action: Fermilab is requested to analyze the resistance of the thermal shield to buckling due to pressure in the extrusion piping and collapse due to eddy currents during quench.

14. Cold mass support



Two cold mass support rings were analyzed and tested to failure during development. The second support ring tested, which represented the final design most closely, failed under a horizontal load of 23,500 lb (105 kN, or 2.2 times the weight of the heaviest cold mass). The reviewers were concerned that the damage might have actually begun at a lower load with small cracks or strain that propagated with increasing load. They suggested that the test data should be reviewed to investigate this possibility.

Action: Fermilab is requested to review the test data to determine the onset of failure.

15. Alignment tolerances and aperture reductions

Fermilab specifies the position of tube ends to ± 2 mm. There was some concern that the alignment tolerances may be too loose. With ± 2 mm positional tolerance at each pipe end, plus ± 1 mm for the survey and some allowance for the relative positioning of the beam tube, the cumulative stack-up may be too much for the bellows to accommodate. CERN uses ± 0.6 mm for the beam pipe position tolerance. The Fermilab tolerance for the beam tube position is unknown.

The cold mass sags in the middle and at both ends due to its weight and the weight of the corrector magnets that are mounted on some of the ends. The local magnetic axis and beam tube follow the sag but the beam does not, resulting in a loss of effective aperture. The local sag at the ends of the beam tube is increased due to cantilevering across long interconnects. The extremely flexible beam tube bellows are expected to provide little additional support at the ends. It was unknown if the sag significantly reduces the aperture, but it was felt a simple check might clear up the question.

An additional source of aperture reduction arises from welding the cold bore to the cold mass. It was conjectured that the weld could protrude into the inner diameter of the cold bore, possibly creating an obstruction for the insertion of a beam screen.

Action: Fermilab is requested to establish a positional tolerance for the beam tube and confirm that the stack-up of tolerances is within the capability and reliability of the bellows.

Action: Fermilab is requested to evaluate the effect of the sag of the cold mass and cantilevered beam tube, and to work with the CERN Apertures Working Group to determine the effect on the aperture.

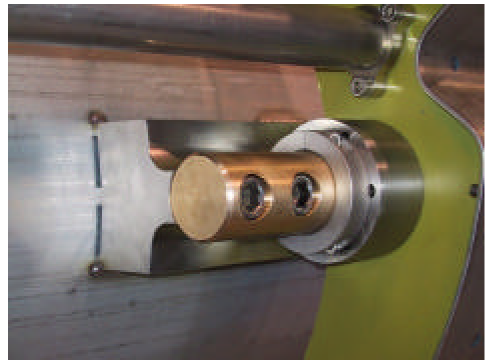
Action: CERN needs to confirm the allowable offsets for beam vacuum bellows.

Action: Fermilab needs to verify the weld interface between the cold bore and cold mass does not result in an aperture reduction.

16. Radiation effects

Fermilab intends to use elastomer seals on the vacuum bellows and a Teflon composite as a bearing material in the cold mass support slides. The effect of radiation, especially near the IP end of Q1, on these materials was not presented. If an elastomer seal cannot be used, a metal O-ring can be used instead.

The Teflon/lead/bronze sliding bearing raised some questions because of the Teflon content. The estimated exposure is 9.5×10^4 Gy over seven years. CERN had previously conducted testing on pure Teflon in similar radiation environments. Teflon degradation in tensile strength was the most pronounced. While degradation is enhanced by the presence of oxygen (which can increase the degradation by two orders of magnitude), the CERN tests were conducted in a nitrogen environment. It is believed that nitrogen and vacuum environments would produce similar results because of the absence of oxygen. The tests indicated moderate damage to pure Teflon under these conditions. CERN still has the capability to perform tests on the sliding material should the need arise. The suggestion was also made to lock the sliding support on Q2P1 during cooldown to simulate a failure of the sliding surface.



There was also some discussion regarding the contact dose that would result after the estimated seven years of quadrupole operating time. It was felt to be particularly relevant in the interconnect region where most of the work would take place during disassembly.

Action: Fermilab and CERN need to determine if radiation degradation testing needs to be performed on the sliding material.

Action: Fermilab is requested to estimate the contact doses for the inner triplet, particularly in the interconnects.

17. Electron cloud effects

The electron cloud effects should be included in the heat load estimates for field free regions.

Action: Subsequent to the review, Fermilab verified that electron cloud effects are included in the heat load table.

18. Vacuum pumping and pressure relief ports

There will be an ISO-K-100 (100 mm) flange for pumping at each interconnect, included as part of the vacuum sleeve, except at the IP end of Q1. This flange can also be used for pressure relief of the vacuum space.

It was unclear during the review how the Fermilab vacuum test requirements compared to those of CERN. Later a copy of the CERN leak tightness specification was provided. The maximum leak rate for the vacuum vessel is 10^{-8} Pa m^3/s (10^{-8} std cc/s). The Fermilab leak rate specification is 10^{-10} Pa m^3/s.

Action: Fermilab needs to include an ISO-K-100 pumping flange in its design for the vacuum pumping port.

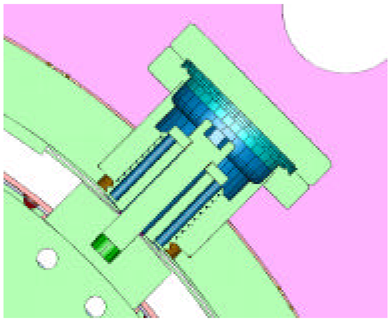
19. Cleanliness of the cold bore

The reviewers pointed out the importance of keeping the cold bore closed at all times for cleanliness. CERN expects to receive the cold bore cleaned and sealed. It was pointed out that CERN has a design for a cold bore protection cover that might be utilized.

Action: Fermilab plans to keep the cold bore closed after cleaning.

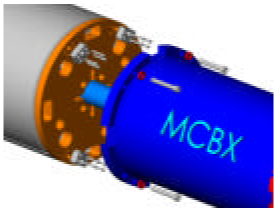
20. Trapped volumes

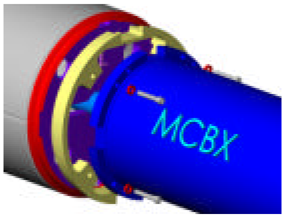
The cold mass supports are attached to the vacuum vessel at four points. The attachment mechanism is somewhat complex and care was taken to design venting of all confined volumes. The discussion included a reminder that trapped volumes must be avoided at those and all other locations.

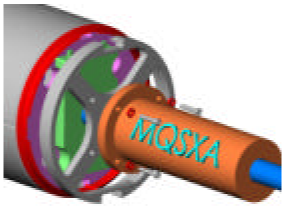


Action: Fermilab intends to confirm that no trapped volumes are present in the design.

21. Alignment of correctors







The correctors are expected to be aligned to 0.5 mm laterally and 5 mrad rotationally. The adjustment is to be achieved by use of oversized holes in the corrector flanges. The lateral alignment would be to the outside diameter of the cold mass skin. The rotational alignment would be to scribe lines. The reviewers expressed concern over the ability of the proposed corrector mounting to meet the alignment requirements. No specific recommendation was made.

Action: Fermilab is requested to evaluate the design of the corrector mounting against the alignment requirements. Fermilab intends to submit a corrector interface specification and the method for alignment should be documented in detail in the specification.

22. Load simulation heaters

Heaters will be installed in the end domes to simulate the dynamic heat loads generated during operation. They are used to help stabilize the cooling system as the beam is brought online. The size and configuration of the heaters has not been finalized. This needs to be done to complete the allocation of space within the end domes.

Action: Fermilab needs to determine the size and configuration of the load simulation heaters with CERN.

23. Helium inventory

CERN requested a summary of helium inventory through the triplet. The summary should include a volume distribution, pipe by pipe.

Action: Fermilab is requested to specify the volume distribution of helium throughout the triplet.

24. BPM location and interfaces

The decision has been made to move a BPM from the non-IP end of Q2, between Q3 and Q2, to the IP end, between Q1 and Q2. The decision still needs to be reviewed and approved through the CERN Engineering Change Request system. The impact on the Q2 is to move it 250 mm further away from the IP. At the time of the review, the details of the BPM design are unknown. Fermilab is working with a conceptual design length of 298 mm provided a year ago. The radial stay-clear area is unknown, but it would have to be limited by the proximity of the nearby cold mass bellows.

Action: CERN needs to develop details of the BPM to enable Fermilab to complete the detailed design of the interconnect region.

Action: CERN needs to complete the Engineering Change Request process to formalize the change of BPM location.

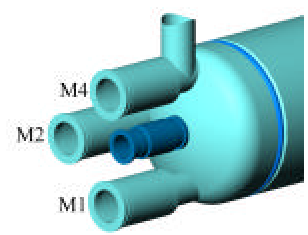
25. Cryostat bellows sleeves

The optimal location of bellows sleeves still needs to be determined. The arrangement of vacuum sleeves versus vacuum bellows, affects vacuum ports and BPM feedthroughs.

Instrumentation routing was not discussed. Fermilab pointed out that instrumentation inside the helium will be routed through the DFBX. Instrumentation outside the helium will be routed through the cryostat to the DFBX, except for BPM cables and possibly liquid level indicators in the IP end of Q1. Completion of the design of the routing of the BPM cables is particularly important, as these specialized cables must be ordered to a specific length (the current order is for 125 cm long cables).

Action: Fermilab needs to complete the design of the bellows sleeves and instrumentation routing.

26. Heat exchanger pipes



Fermilab is increasing the size of heat exchanger pipes (M4) in the interconnect region and their vertical risers from 3½ in. (89 mm) to 4 in. (102 mm) in diameter. This will facilitate better heat transport and reduce the temperature drop.

Action: Fermilab is asked to provide CERN with details of the redesign of the heat exchanger connecting pipes.